

# Revised tectonic boundaries in the Cocos Plate off Costa Rica: Implications for the segmentation of the convergent margin and for plate tectonic models

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**Abstract.** The oceanic Cocos Plate subducting beneath Costa Rica has a complex plate tectonic history resulting in segmentation. New lines of magnetic data clearly define tectonic boundaries which separate lithosphere formed at the East Pacific Rise from lithosphere formed at the Cocos-Nazca spreading center. They also define two early phase Cocos-Nazca spreading regimes and a major propagator. In addition to these sharply defined tectonic boundaries are overprinted boundaries from volcanism during passage of Cocos Plate over the Galapagos hot spot. The subducted segment boundaries correspond with distinct changes in upper plate tectonic structure and features of the subducted slab. Newly identified seafloor-spreading anomalies show oceanic lithosphere formed during initial breakup of the Farallon Plate at 22.7 Ma and opening of the Cocos-Nazca spreading center. A revised regional compilation of magnetic anomalies allows refinement of plate tectonic models for the early history of the Cocos-Nazca spreading center. At 19.5 Ma a major ridge jump reshaped its geometry, and after ~14.5 Ma multiple southward ridge jumps led to a highly asymmetric accretion of lithosphere. A suspected cause of ridge jumps is an interaction of the Cocos-Nazca spreading center with the Galapagos hot spot.

## 1. Introduction

The Central America convergent margin off Costa Rica and Nicaragua has been an area of concentrated study during the past decade because of its variable character in a relatively small area and its well-imaged subduction zone. Recent publications report a distinctive segmentation of the upper plate tectonic structure and relate much of this to a corresponding segmentation of the subducting Cocos Plate. This segmentation was recognized in a progression of studies each contributing to an increasing understanding of the tectonic origin of each plate segment. The existence of a rough and a smooth morphological domain on the Cocos Plate was noted in the early 1960s [Fisher, 1961] (Figure 1). In the early 1990s a comprehensive multibeam bathymetric survey of ocean crust was made off Costa Rica [von Huene *et al.*, 1995]. This study showed sharp boundaries between three morphological segments on the oceanic plate: (1) smooth seafloor facing the Nicoya Peninsula, (2) a segment with abundant (40%) seamounts to the southeast, and (3) Cocos Ridge entering the subduction zone off Osa Peninsula along the southern Pacific coast of Costa Rica. It became clear that the roughness of the seafloor significantly affects the shape and the tectonics of the

continental slope [von Huene *et al.*, 1995; Hinz *et al.*, 1996], and even forearc uplift nearshore [Fisher *et al.*, 1998]. The down-going slab along Central America changes dip significantly [Protti *et al.*, 1995a], and the geochemistry of arc volcanic rocks and the alignment of volcanoes changes similarly [e.g., Carr and Stoiber, 1990; Patino *et al.*, 2000]. A recent study shows the degree to which character and relief of the subducting lower plate relates to upper plate tectonism and arc volcanism [von Huene *et al.*, 2000]. However, precise age information and identification of tectonic boundaries of the Cocos Plate are lacking. In this study, we focus on the integration of new data with previously published compilations [Barckhausen *et al.*, 1998] that answer some of these questions. We present a detailed magnetic anomaly map including ~8000 km of new data and analyze the tectonic setting of the study area in the framework of the regional magnetic seafloor-spreading anomalies. This constrains crustal age and precise location of major tectonic boundaries. The crustal ages permit us to revise the plate tectonic history of the Cocos-Nazca spreading center (CNS) from the breakup of the Farallon Plate at 23 Ma to 10 Ma.

## 2. Previous Work

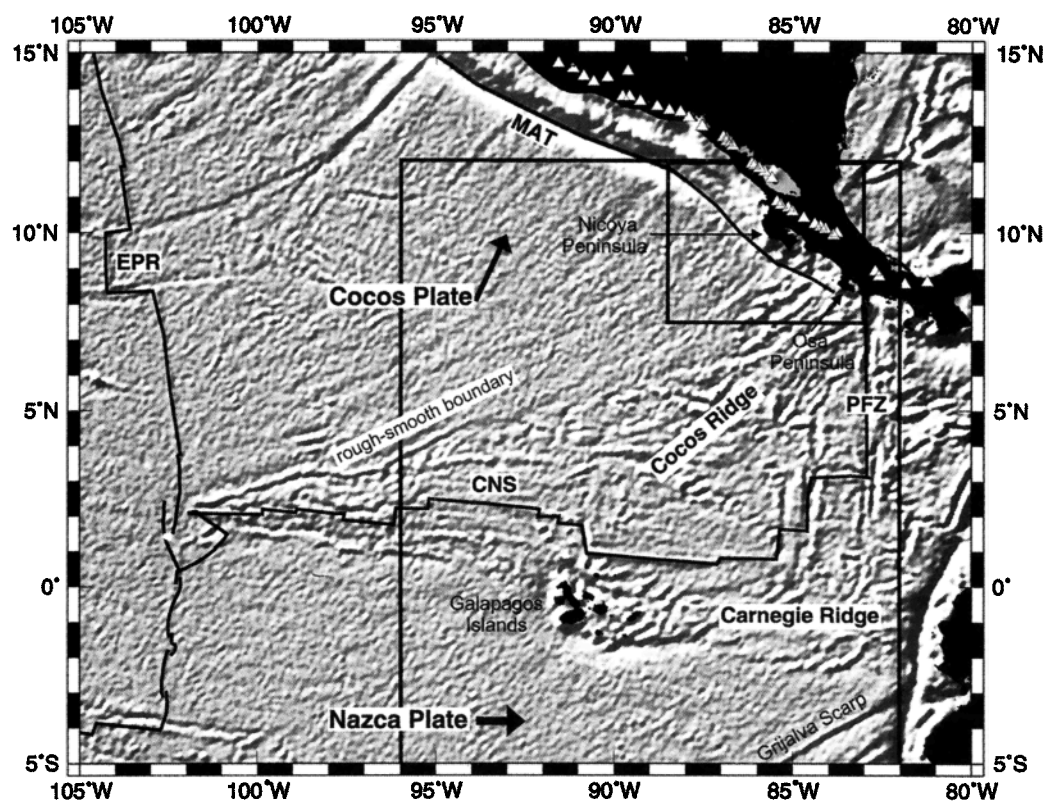
The first consistent models of CNS evolution and the formation of the aseismic Cocos and Carnegie ridges were derived by Hey [1977] and Lonsdale and Klugord [1978]. From the analysis of magnetic and bathymetric data they concluded that the Farallon Plate broke into the Cocos and Nazca Plates along a preexisting fracture zone in equatorial regions at ~27 Ma. According to this model the newly formed CNS interacted with the Galapagos hot spot, which simultaneously deposited volcanic material on both sides of the CNS to feed the Cocos and Carnegie Ridges on the Cocos and Nazca plates. Magnetic seafloor-spreading anomalies had been identified in the inner region of the CNS along the active spreading axis and south of

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**Figure 1.** Bathymetric map of the Cocos-Nazca spreading region based on satellite altimetry of *Smith and Sandwell* [1997]; EPR, East Pacific Rise; CNS, Cocos-Nazca spreading center; PFZ, Panama Fracture Zone; MAT, Middle America Trench. Arc volcanoes in Central America are shown as triangles. Arrows indicate absolute plate motion vectors [DeMets *et al.*, 1990]. The rough-smooth boundary is expressed clearly only in the western part of the CNS region. The small rectangle outlines the area in Plate 1 and Figure 4; the large rectangle indicates the area covered by Plate 2.

the Carnegie Ridge. In the areas of the submarine ridges that were overprinted by hot spot related volcanic activity no lineated anomalies could be identified. North of Cocos Ridge the identification of seafloor-spreading anomalies was also impossible at that time because of the paucity of data and complicated anomaly pattern [Hey, 1977]. Later, *Wilson and Hey* [1995] revised the magnetic anomalies of the inner part of the CNS and carefully documented anomalies younger than 10 Ma, including a pattern of propagators and small ridge jumps.

Today, oceanic crust along the west and south boundaries of the Cocos Plate is generated by active spreading along the East Pacific Rise (EPR) and the CNS. Oceanic crust formed at the EPR has the featureless morphology and low-amplitude magnetic anomalies common to fast-spreading ridges [Hey, 1977; Wilson, 1996]. Oceanic crust currently generated at the CNS near the triple junction with the EPR is formed by slow spreading. It has a rough topography and high-amplitude magnetic anomalies [Wilson and Hey, 1995]. Hey [1977] mapped the resulting "rough-smooth boundary," separating two provinces formed at two different spreading centers within the Cocos Plate (Figure 1). Hey [1977] projected the rough-smooth boundary from the seaward area where it is well expressed, landward to the southern tip of the Nicoya Peninsula. However, since no seafloor-spreading anomalies could be identified in the area off Costa Rica, the location of the boundary was defined from bathymetric observations [Hey, 1977]. In addition, Hey [1977] pointed out that in the older part of the CNS-derived Cocos Plate crust the magnetic and bathymetric

rough-smooth boundaries are genetically different and do not necessarily coincide. Near the Middle America Trench (MAT) the fine-scale topography of the oceanic basement is fairly smooth, and the rough-smooth boundary was defined at the limit between an oceanic domain with numerous hotspot related volcanic edifices (ridges, conical volcanoes, and guyots) [von Huene *et al.*, 1995] and a domain with smooth topography. *Barckhausen et al.* [1997] showed that magnetic anomalies of the CNS continue north of the morphological rough-smooth boundary, but the exact position of the boundary between EPR- and CNS-generated crust was not clear from the magnetic anomaly data. The magnetic anomaly map compiled from data acquired during cruise SO-76 [Barckhausen *et al.*, 1998] showed two different patterns of seafloor-spreading anomalies off Costa Rica, both being attributed to the CNS. However, since the survey area was relatively small and the magnetic signatures of numerous seamounts are superimposed upon the linear anomalies, it was still impossible to identify seafloor-spreading anomalies and clearly define tectonic boundaries in the oceanic crust. Wilson [1996] analyzed seafloor-spreading anomalies on the EPR-derived part of the Cocos Plate along the rough-smooth boundary between 94°W and 88°W but did not extend the identification of anomalies and the triple junction trace eastward to the MAT.

The bathymetric rough-smooth boundary has been widely used by different authors as the trace of the triple junction of EPR and CNS off Costa Rica and inferred as a major lithospheric feature that explains patterns in the configuration of the

subducting slab along the continental margin [e.g., *Protti et al.*, 1995a; *Marshall et al.*, 2000; *Patino et al.*, 2000]. The boundary between the seamount domain and the smooth domain is marked by a tectonic boundary that is shown in seismic data as an abrupt but small jump in the depth of the top of the basement and the base of the crust [*von Huene et al.*, 2000]. Therefore there are at least two tectonic boundaries in our study area: the traditional rough-smooth boundary associated with a tectonic scarp and the trace of the triple junction between Pacific, Cocos, and Nazca plates.

### 3. New Data

Our study is based on magnetic data from the cruises SO-76 [*von Huene et al.*, 1992], SO-107 [*Mrazek et al.*, 1996], Revelle delivery cruise (R. Knox, unpublished report, 1996), SO-144/1 [*Bialas et al.*, 1999], SO-144/3 [*Werner et al.*, 2000], and BGR-99 [*Reichert et al.*, 2000]. The SO-76 data were previously processed well enough to reduce the RMS crossover error to <10 nT [*Barckhausen et al.*, 1998]. The remaining data were averaged to produce along-track values at 20 s intervals. The averaging process included a procedure to eliminate spurious values. Positions were corrected for the distance from ship to sensor, and anomalies were calculated by subtracting the geomagnetic reference field IGRF 95 [*International Association of Geomagnetism and Aeronomy (IAGA)*, 1996]. To correct for magnetic daily variations arising from ionospheric currents, we digitized analogue magnetograms obtained from the geomagnetic observatory Tilaran, Costa Rica, which is located at a distance between 50 and 350 km from the surveyed profiles. The scalar field was calculated ( $\Delta F = \Delta Z \sin I + \Delta H \cos I$  for small declinations) and subtracted from the data. Since the sensors had been towed at distances exceeding three ship's lengths from the research vessels in all cases, corrections of heading effects were not necessary. After processing, the new data also have low crossover errors like the SO-76 data. The zero levels of all data sets were adjusted to that of the SO-76 data at crossovers, and the data files were then merged.

The resulting total field magnetic anomalies (Plate 1) show three zones with different magnetic anomaly patterns: (1) In the northwest offshore Nicaragua, northern Costa Rica, and the northern half of the Nicoya Peninsula, relatively weak anomalies generally parallel the MAT inasmuch as the pattern is observable. The high-amplitude anomalies in a small zone northwest of Nicoya Peninsula are derived from a shallow upper plate basement. (2) In a strip only ~90 km wide that faces the southern half of the Nicoya Peninsula, clearly defined linear anomalies trend N50°E and extend from the ocean basin landward to the end of the profiles. (3) In the southeastern part, linear anomalies with significantly stronger amplitudes strike N70°E. Superimposed are local anomalies caused by seamounts. In the area of Cocos Ridge in the southeastern-most corner of the survey area the pattern becomes irregular. On the basis of previous investigations [*Hey*, 1977; *Wilson*, 1996] it seems obvious that the oceanic crust in the northwestern part of the survey area was formed at the EPR, whereas the two SW-NE trending anomaly patterns must be attributed to oceanic crust formed at the CNS. The EPR-CNS boundary separating the lithospheric provinces formed at different spreading ridges deviates from the morphological rough-smooth boundary. This fact has led to confusion among researchers in the area. Because the rough-smooth morphological proxy breaks down near the continent, we will use the

following terms for the boundary between the EPR- and CNS derived provinces: The younger part of the boundary which formed after the breakup of the Farallon Plate at the Ridge-Ridge-Ridge triple junction will be called "triple junction trace." The older part of the boundary along the fracture zone where the Farallon Plate broke up is called "fracture zone trace." The triple junction trace has an oblique angle to both the EPR- and the CNS-derived magnetic anomalies, and crustal ages are equal to both sides of the trace. The fracture zone trace parallels the CNS magnetic anomalies and is a discontinuity with no age progression along the CNS side and increasing ages along the EPR side of the trace.

Looking at the map (Plate 1) in more detail, it is apparent that the N50°E and the N70°E striking anomalies are in discordant contact along a line that parallels the N70°E direction. This is likely to be the result of a ridge jump breaking through the old pattern during the early history of the CNS. Such an early ridge jump with a significant change of the strike direction was discussed by *Hey* [1977] and is also proposed in a model by *Meschede et al.* [1998]. Just south of the discordance the N70°E striking anomalies seem to be offset along a morphological and tectonic feature called Fisher Ridge [*von Huene et al.*, 2000] (Figure 2). The point where the two supposed tectonic lines meet off the southern tip of the Nicoya Peninsula coincides with the prominent Fisher Seamount (Figure 2).

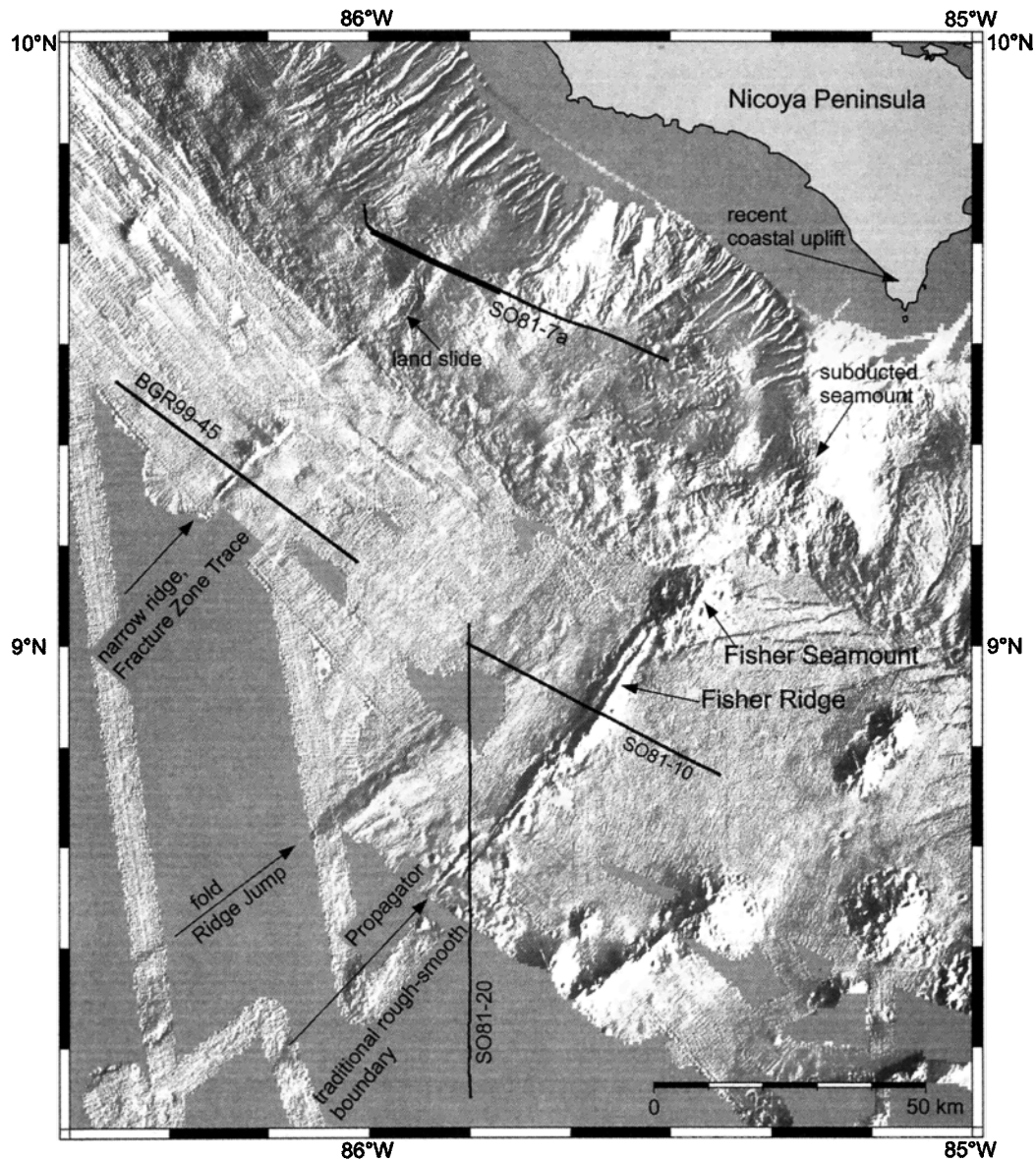
The area of mapped magnetic anomalies off Central America has more than doubled since the SO-76 data were collected. Although the anomaly patterns have become much clearer, the map is still not extensive enough to clearly identify seafloor-spreading anomalies. In order to decipher the complicated plate tectonic configuration it is instructive to look at the magnetic anomalies at a larger scale.

### 4. Regional Framework

Seafloor-spreading anomalies are reliably identified only in part of the CNS area. Between 96°W and 84°W, CNS-derived anomalies from recent to 4A (0–10 Ma according to the magnetic polarity timescale of *Cande and Kent* [1995]; this timescale is used throughout this paper) have been mapped thoroughly on both sides of the active CNS [*Wilson and Hey*, 1995]. Along the northern triple junction trace EPR-derived anomalies 5A through 6A (12–21 Ma) have been identified between 94°W and 88°W [*Wilson*, 1996]. The gap between the areas covered by these two studies is <50 km wide at 95°W and broadens to ~550 km at 88°W. CNS-derived anomalies older than 4A which must be present in this gap have proven extremely difficult to correlate [*Hey*, 1977; *Wilson and Hey*, 1995].

In order to fill as much as possible of this area with reliable magnetic anomaly identifications we first extended the correlation of EPR-derived anomalies along a stripe north of the triple junction trace and eastward to the MAT. We found a reasonable correlation for anomalies 6A to 6C on a number of profiles including two profiles from our new data (Figure 3a). This more complete knowledge of crustal ages along the triple junction trace also provides age control for CNS-derived magnetic anomalies just south of the triple junction trace. It is a basic requirement for a Ridge-Ridge-Ridge-type triple junction configuration that crustal ages along the triple junction trace are equal on both sides of the boundary.

With the knowledge of the position and age progression of the triple junction trace on the northern side and the position of anomaly 4 or 4A on the southern side it was possible to fill



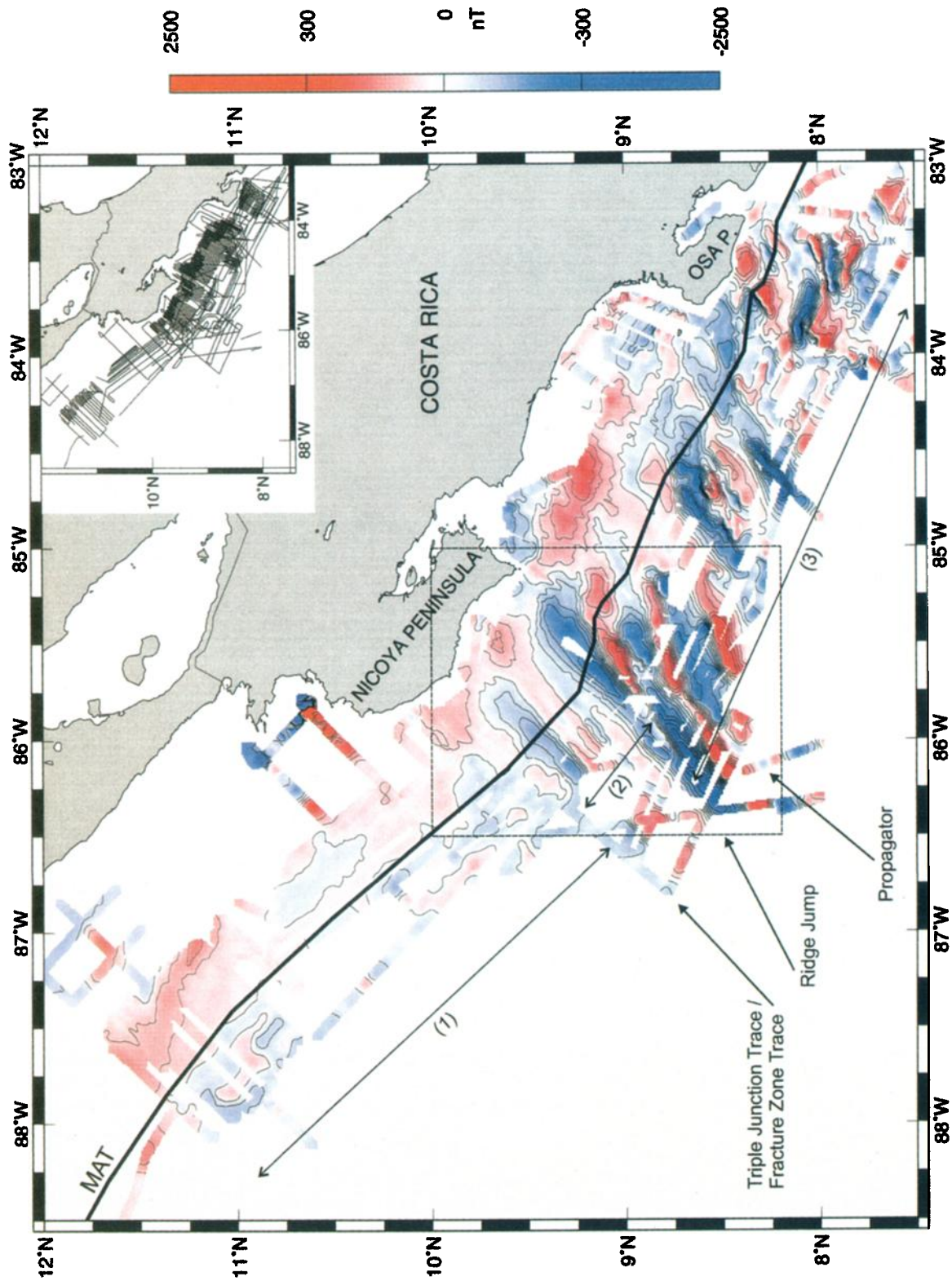
**Figure 2.** High-resolution multibeam bathymetry map of the study area (100 m grid). The data were collected during R/V *Sonne* cruises 76, 107, and 144 and R/V *Revelle* transit. Tracks of multichannel seismic reflection data in Figures 6a, 6b (thick segment along track line 7a), 6c, and 6d are shown. The scarp of the narrow ridge marks the boundary between the lithosphere formed at the East Pacific Rise and the Cocos-Nazca spreading center. This boundary of the ocean plate corresponds to a small landslide in the lower slope and is also imaged on track line 7a as a step in the plate boundary beneath the slope (see Figure 6b). The ridge jump and the propagator are explained in the text.

major parts of the gap between the studies of *Wilson and Hey* [1995] and *Wilson* [1996]. We selected several single magnetic profiles heading approximately parallel to the tectonic flow lines from data available from the *National Geophysical Data Center (NGDC)* [1998] data compilation and from the *Scripps Institution of Oceanography's* database (2000). Research vessels passing the survey area at different times have taken the profiles, and the errors along them are not well documented. We examined all data for spurious values and subtracted the mean value from each profile. Having two points with known age on each of these profiles, it was possible to identify the seafloor-spreading anomalies between 4A and the triple junction trace in the area between 96°W and ~89°W. The anomalies trend N70°E, like those mapped off southern Costa Rica (Plate

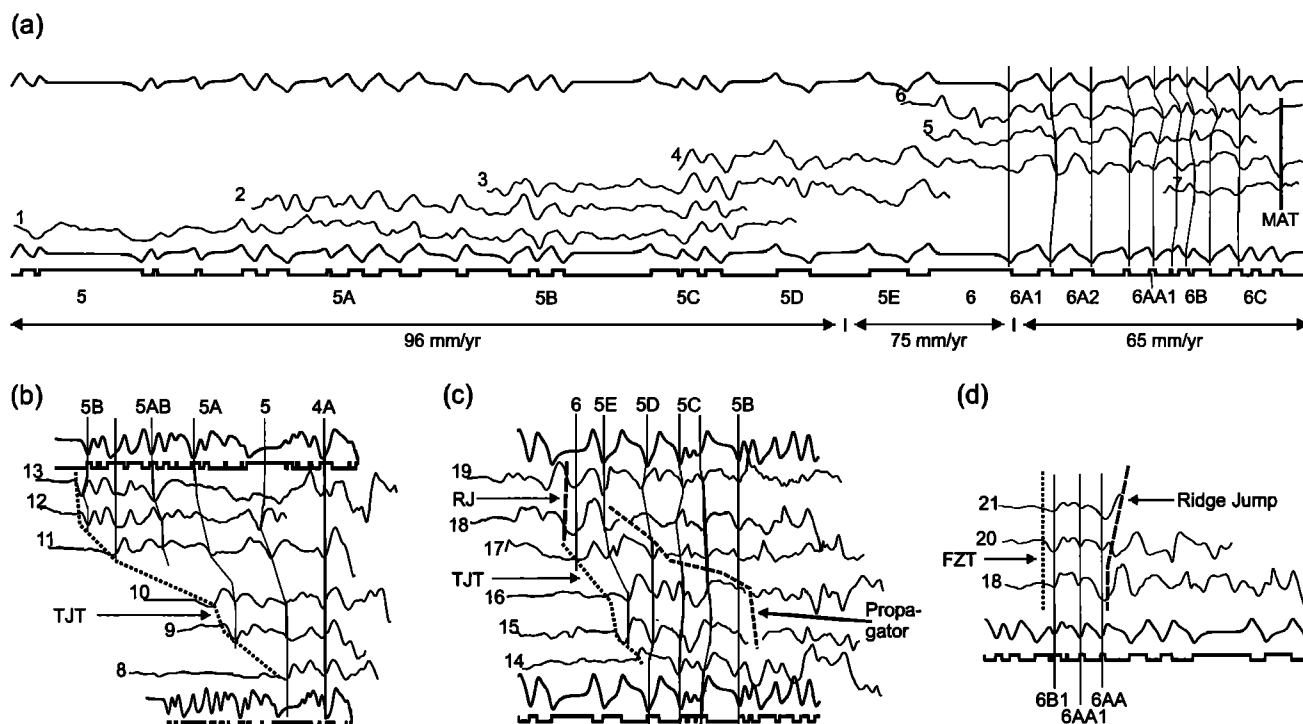
2). We found half-spreading rates increasing from 20 mm/yr at 95°W to 30 mm/yr at 90°W (Figure 3b). These spreading rates are higher than those *Wilson and Hey* [1995] found for the time period 5.23 Ma to 10 Ma (14 mm/yr at 95°W and 21 mm/yr at 90°W), but the increase toward the east matches the findings in the younger anomalies very well. With the existing data we have not been able to map propagators and transform faults in detail.

East of 89°W, reconstruction is difficult for two reasons. First, the irregular pattern of magnetic anomalies associated with Cocos Ridge interrupts anomalies in the south and the triple junction trace in the north, obstructing correlation of the seafloor-spreading anomalies. Second, east of 89°W the distances between the oldest identified anomalies south of the Cocos Ridge and the triple junction trace are much larger than





**Plate 1.** Magnetic anomaly map of the survey area. Three different patterns of magnetic anomalies are distinguishable: (1) weak N115°E striking anomalies offshore Nicaragua and northern Costa Rica, (2) N50°E striking anomalies off the southern half of the Nicoya Peninsula, and (3) a N70°E striking, less regular pattern adjacent to the southeast. The inset shows the ship tracks; MAT, Middle America Trench. Contour interval is 50 nT. The tectonic boundaries are explained in the text. The rectangle indicates the area covered by Figure 2.



**Figure 3.** (a) Correlation of magnetic anomaly profiles taken north of the triple junction trace/fracture zone trace with a synthetic profile calculated from a 500 m thick source layer at 4000 m water depth. Spreading rates for ages <20 Ma are from Wilson [1996]. For location of the profiles, see Figure 3f; MAT, Middle America Trench. (b) Correlation of magnetic anomaly profiles taken north of the CNS with synthetic profiles calculated from a 500 m thick source layer at 3000 m water depth. Spreading rates are 20 mm/yr at the bottom and 30 mm/yr at the top of the figure. For location of the profiles, see Figure 3f; TJT, triple junction trace. (c) Continuation of Figure 3b. For location of the profiles see Figure 3f. The spreading rate is 35 mm/yr; RJ, ridge jump. (d) Correlation of magnetic anomaly profiles taken off the southern half of the Nicoya Peninsula with a synthetic profile calculated from a 500 m thick source layer at 3500 m water depth. For location of the profiles see Figure 3f; FZT, fracture zone trace. These magnetic anomalies record the onset of the opening of the CNS. On the Cocos Plate they are only preserved in a small area off Costa Rica. (e) Correlation of magnetic anomaly profiles taken west of the Galapagos Islands with synthetic profiles calculated from a 500-m-thick source layer at 3000 m water depth. Spreading rates are 30 mm/yr at the bottom and 42 mm/yr at the top of the figure. The westernmost profile is at the bottom of the figure (cf. Plate 2). (f) Location map of the profiles modeled in Figures 3a–3d. All profiles are shown as wiggle traces in Plate 2.

spreading rates found farther west. Either the spreading rate was much higher (close to 60 mm/yr half-spreading rate) in this area or another tectonic system prevailed. A likely candidate is a significant ridge jump at ~14.5 Ma proposed in a model by Meschede *et al.* [1998]. Despite these problems it was still possible to tie magnetic anomalies at the triple junction trace with known ages. We were able to correlate anomalies 5B and older in the area east of 89°W at spreading rates of 35 mm/yr, without an increase of spreading rates eastward (Figure 3c). The oldest of the N70°E striking anomalies is anomaly 6. This anomaly can be traced into the mapped area off Costa Rica, where it is in contact with the N50°E striking anomalies, thus dating the inferred ridge jump at ~19.5 Ma. The N50°E striking anomalies can easily be correlated with anomalies 6AA through 6B1 at a half-spreading rate of 50 mm/yr (Figure 3d). We found no evidence for anomalies older than 6B1 generated at the CNS. During cruise BGR-99 one magnetic profile heading parallel to the N50°E striking anomalies was taken just north of the inferred position of the triple junction trace/fracture zone trace. This profile clearly shows EPR-derived magnetic anomalies 6B and older (profile 7 in Figure 3a). This proves that there was no triple junction configuration prior to

anomaly 6B, and that instead, the boundary between EPR- and CNS-derived anomalies parallels anomaly 6B1 off northern Costa Rica. Therefore, for this part of the boundary the term “fracture zone trace” applies as it is the discontinuity that represents the initial Farallon Plate breakup.

In order to complete the picture the proposed identifications of old CNS-derived seafloor-spreading anomalies on the Cocos Plate must be compared to those on the Nazca Plate south of the Carnegie Ridge. In this area, Hey [1977] identified seafloor-spreading anomalies paralleling the northern flank of the Grijalva Scarp which separates oceanic lithosphere formed at the EPR and at the CNS on the Nazca Plate (Figure 1). He suggested those anomalies might be remnants of the initial opening of the CNS along a preexisting fracture zone. As a test of this interpretation, Hey [1977] proposed that a boundary counterpart to the Grijalva scarp must be found east of 88°W on the Cocos Plate off Costa Rica. We reexamined the magnetic anomalies north of the Grijalva Scarp. Our interpretation differs only slightly from that given by Lonsdale and Klitgord [1978], who correlated the oldest CNS anomaly just north of the Grijalva Scarp with anomaly 6B. This matches exactly the oldest of the N50°E striking anomalies off Costa Rica. We

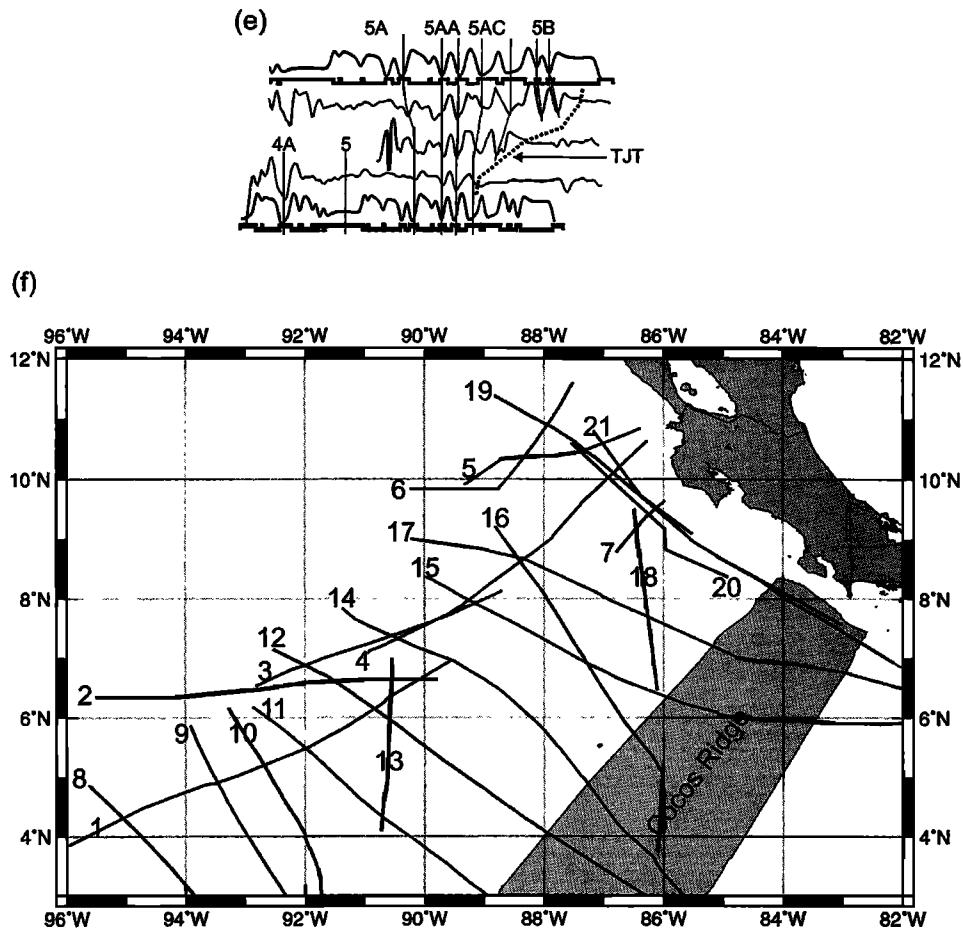


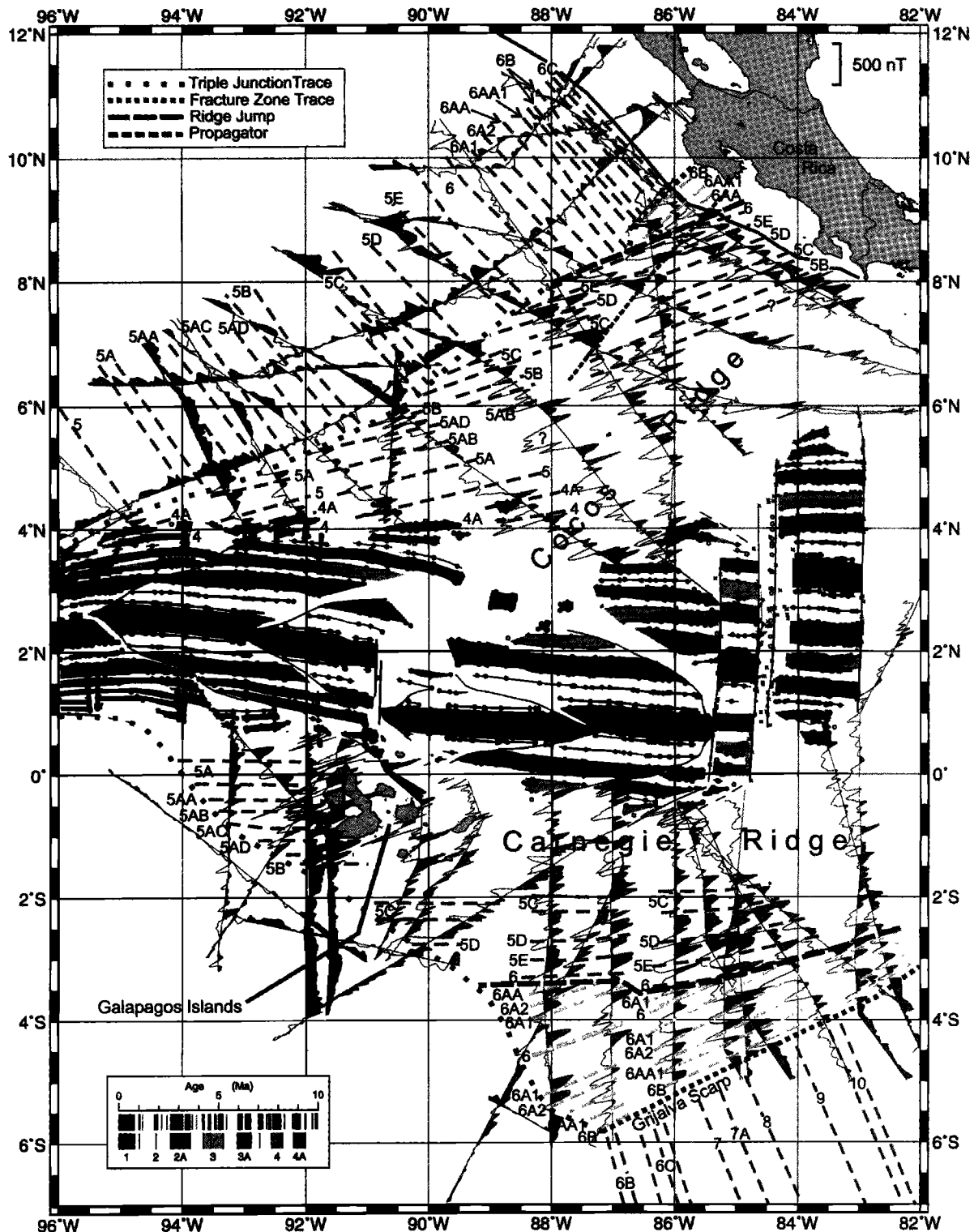
Fig. 3. (continued)

conclude that the N50°E anomalies off Costa Rica are the mirror image of those north of the Grijalva Scarp and thus represent the remaining record of the initial opening of the CNS on the Cocos Plate, located exactly where Hey [1977] suspected them to be. In agreement with Lonsdale and Klitgord [1978] we find that anomalies 6B1 through 6A1 parallel the Grijalva Scarp striking N65°E at a half-spreading rate of 45 mm/yr. Anomalies 6 and younger trend ~E-W and can be correlated northward up to anomaly 5C at a half-spreading rate of ~40 mm/yr. This configuration leaves a blank wedge-shaped piece of crust between the N65°E striking anomaly 6A1 and the E-W striking anomaly 6. Lonsdale and Klitgord [1978] called this a "region of rise jumps." Even though magnetic anomalies in this region are not clear without any new magnetic profiles since 1978, we suggest that the wedge-shaped piece of crust represents the missing part of the N50°E striking anomalies off Costa Rica. The abandoned spreading axis that has been transferred to the Nazca Plate by the ridge jump at 19.5 Ma discussed earlier would be included in that area.

West of the Galapagos Islands, CNS-derived magnetic anomalies 5A through 5B with a half-spreading rate of ~35 mm/yr (Figure 3e) were identified in some recently acquired magnetic profiles. These anomalies are the undisturbed continuation of the younger anomalies identified by Wilson and Hey [1995], similar to those north of the CNS and west of 89°W. East of the Galapagos Islands the Carnegie Ridge prohibits correlation of magnetic anomalies younger than 5C northward into the area mapped by Wilson and Hey [1995].

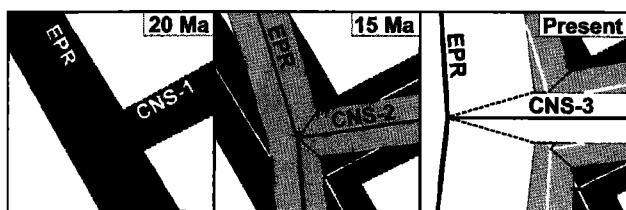
However, the distance between anomalies 2A and 3 north of the ridge and 5C south of it is clearly too small to allow a continuous accretion of crust between them. Hey [1977] had already noted that the highly asymmetric accretion of oceanic lithosphere along the eastern part of the CNS cannot be explained by asymmetric spreading rates and discussed the possibility of a series of southward ridge jumps. Wilson and Hey [1995] confirmed this explanation for ages <10 Ma. It is likely that similar ridge jumps occurred earlier. The question is, was there a series of small ridge jumps or one major ridge jump between anomalies 5B and 5. The latter was proposed in the model by Meschede et al. [1998]. Since we found nearly symmetric spreading rates in the time interval between anomaly 6 and 5C on both sides of the CNS and no indications of small ridge jumps, we speculate that a ridge jump similar to the one at 19.5 Ma occurred shortly after anomaly 5B at ~14.5 Ma. However, since these discordances are buried under the Cocos and Carnegie Ridges, there is little evidence to definitively answer this question.

Assuming a major ridge jump at 14.5 Ma in addition to the confirmed jump at 19.5 Ma splits up the spreading history of the CNS into three stages which have been termed CNS-1 (22.7–19.5 Ma), CNS-2 (19.5–14.5 Ma), and CNS-3 (14.5–recent) by Meschede et al. [1998]. Since these terms have been used already by others [e.g., von Huene et al., 2000], we continue using them here. Figure 4 is a schematic sketch that summarizes the three-stage evolution of the CNS.



**Plate 2.** Magnetic anomalies [NGDC, 1998; Scripps Institution of Oceanography database (2000); this study] in the area of the CNS between 96°W and 82°W shown as wiggles with positive anomalies shaded above the track line. Profiles with gray shaded anomalies are from the NGDC and Scripps sources; profiles with solid shaded anomalies are new data compiled here. The interpretation of younger anomalies at the center of the map is from *Wilson and Hey [1995]*; see legend in the lower left corner. Green dashed lines indicate seafloor-spreading anomalies formed at the EPR. Red dashed lines mark magnetic anomalies derived from CNS-1. Blue dashed lines indicate magnetic anomalies formed at the CNS-2 after a ridge jump at 19.5 Ma. EPR-derived magnetic anomalies 6B through 10 south of the Grijalva Scarp after B. Eakins (unpublished data, 2000). The interpreted magnetic anomalies, paleo plate boundaries, ridge jumps, and propagators reveal a complicated plate tectonic history.





**Figure 4.** Schematic sketch of the evolution of the CNS in three stages.

## 5. Discussion

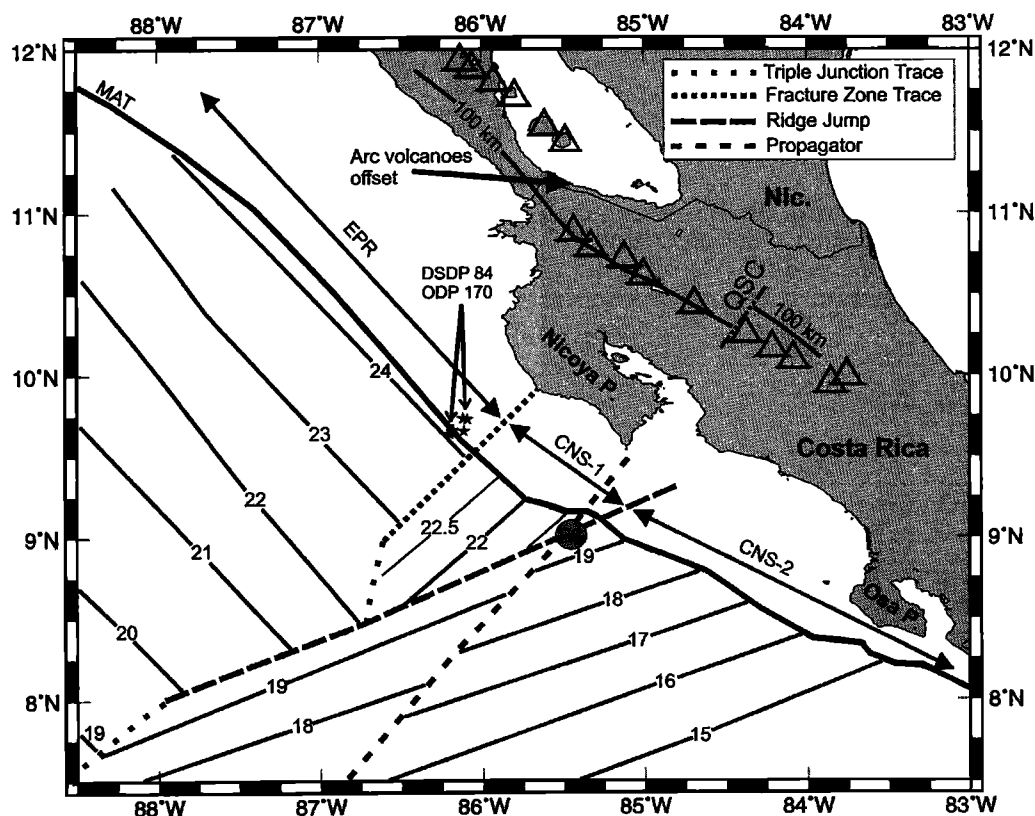
### 5.1. Crustal Ages and Tectonic Boundaries off Costa Rica

Our revised magnetic anomaly map provides crustal ages and defines three tectonic boundaries off Costa Rica (Figure 5). (1) The ~80 km long fracture zone trace separating EPR crust from CNS crust is orthogonal to the MAT off the central Nicoya Peninsula (Plate 2 and Figure 5). (2) The ridge jump from CNS-1 to CNS-2 results in a tectonic boundary paralleling anomaly 6. This boundary marks an age jump of 1.9 m.y. (chron 6n to 6A2r) at the MAT. (3) A ~35 km offset of magnetic anomalies occurs along a structure that strikes oblique to the ridge jump (Figure 5). The oblique trend of this structure and the lateral displacement of anomalies indicate a propagator similar to those in young crust on either flank of the CNS [Wilson and Hey, 1995] (Plate 2).

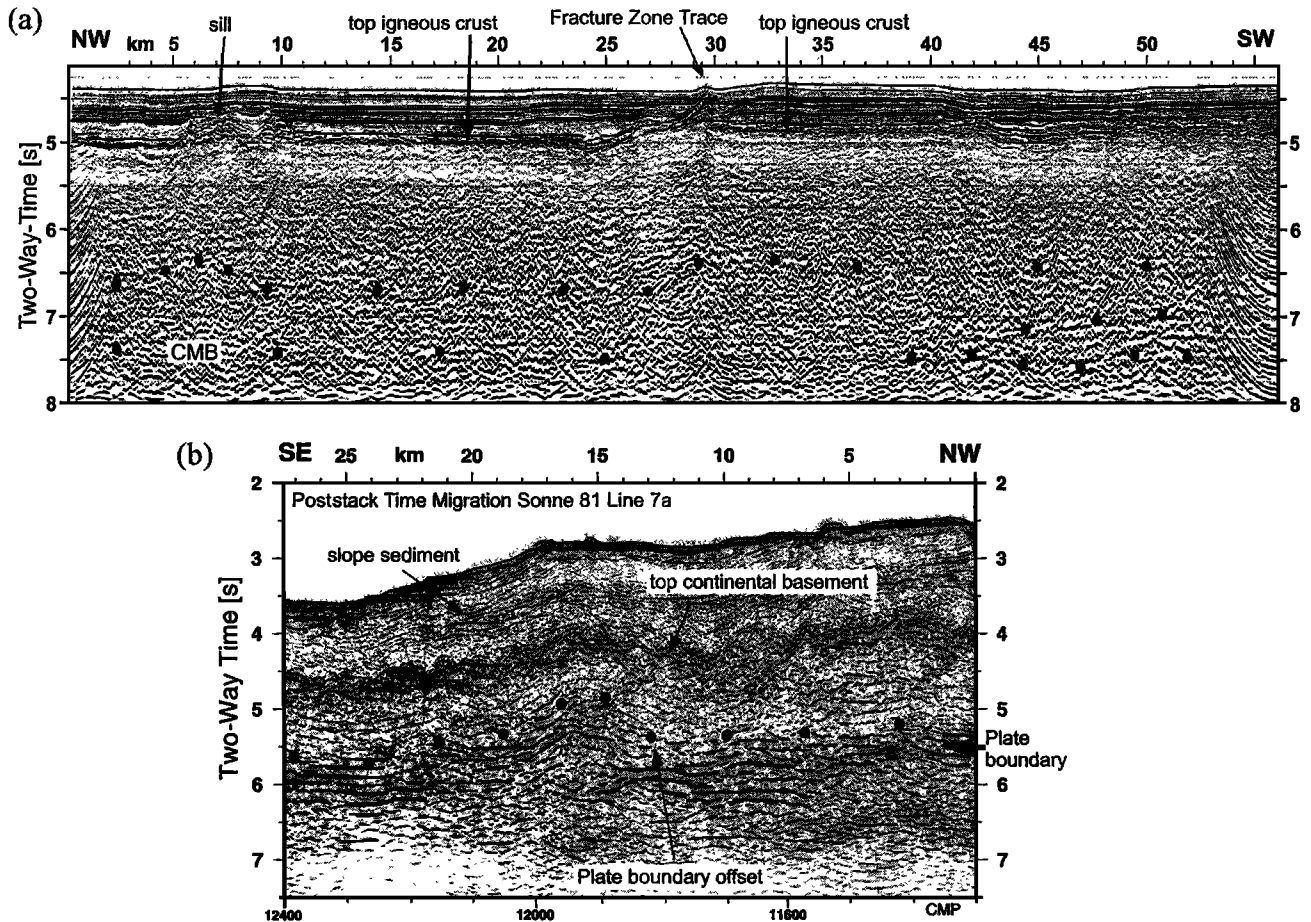
The three tectonic boundaries mapped with magnetic data

are also topographic features observed in multibeam bathymetry and crustal structure in seismic sections:

1. The NW flank of the fracture zone where the CNS initially opened corresponds to a narrow ridge across the oceanic plate (Figure 2). A seismic reflection image across the fracture zone trace indicates lateral continuity even where sediment buries the ridge. The ridge is the culmination of a ~5 km wide tilted basement block with a smooth upper surface (Figure 6a). Overlying strata onlap the tilted block, indicating basement tectonism prior to sediment deposition. Surprisingly, this lithospheric boundary shows only a minor change in crustal structure. Weak reflections from the crust-mantle boundary appear at about the same two-way time on either side of the seafloor scarp, and only a small change in lower crust reflections occurs across the boundary (Figure 6a). The smooth upper surface of the oceanic igneous crust across the boundary indicates that during opening, magmatism and deformation rapidly nucleated into the new spreading center and that during breakup the Farallon crust experienced little vertical displacement. The ridge appears to continue across the trench beneath the continental slope and coincides with seafloor instability (Figure 2). A seismic reflection strike line across the slope and parallel to the trench shows an offset at the plate boundary, indicating the subducted extension of the ridge (Figure 6b). The plate boundary reflections most likely come from subducted sediment cover of the ocean plate and perhaps material eroded from the upper plate [Ranero and von Huene, 2000], making it difficult to estimate the dimensions of the ridge. Although the expres-



**Figure 5.** Isochron map of the study area off Costa Rica with ages derived from identification of seafloor-spreading anomalies. Numbers indicate crustal ages in m.y. Tectonic boundaries and the locations of the Deep Sea Drilling Project Leg 84 and Ocean Drilling Program Leg 170 drill holes are indicated. Triangles show the locations of arc volcanoes; FS, Fisher Seamount; QSC, Quesada Sharp Contortion. The 100 km isobath of the Wadati-Benioff zone is added [after Protti et al., 1995a].



**Figure 6.** Poststack finite differences time migrations of multichannel seismic reflection lines across several tectonic boundaries of the Cocos Plate. For location, see Figure 2. (a) Line BGR99-45 across the fracture zone where the initial opening of the Cocos-Nazca spreading center took place. The crust-mantle boundary is defined by some faint reflections at ~7 s two-way time. Lower crustal reflectivity is also observed. (b) Line Sonne-81-7a. The profile runs across the middle slope offshore Nicoya Peninsula. The seismic record shows the plate boundary as a band of low-frequency reflections occurring at 6 to 5.5 s two-way time. The boundary between the lithosphere formed at the Galapagos Spreading Center and the East Pacific Rise is observed as an offset in the plate boundary topography. (c) Line Sonne-81-10. The seismic record images the structure across the Fisher Ridge and the trace of a ridge jump. Recent tectonic activity has uplifted and folded the sedimentary cover and top basement northwest of Fisher Ridge. The fold can also be observed in the bathymetry of Figure 2 and is coincident with the ridge jump mapped with magnetic data (Plate 1), indicating a reactivation of this boundary during subduction processes. Note the onlap of sediment strata on the Fisher Ridge, indicating that the topography was created before the deposit of most sediment. (d) Line Sonne-81-20. This line displays the lateral continuity of structures described in Figure 6c. It also displays the onlap of sediment strata on a seamount.

sion of the boundary between EPR and CNS lithosphere observed at the Middle America Trench is a subdued feature, the subducted extension of the boundary might have been more pronounced. Assuming spreading rates like those measured for the oldest EPR crust off northern Costa Rica and south of the Grijalva Scarp implies that about 1500 km and 900 km of the boundary have been subducted during the last 22.7 m.y. beneath Central America and northern South America, respectively. Thus there was an age jump of at least 20 m.y. across the oldest portion of the fracture zone where the CNS formed. Rejuvenation of a 20 m.y. old lithosphere during the opening and formation of the CNS probably created a topographic feature more prominent than that currently being subducted, and the effect of the collision of such a feature with the continent might have involved important tectonism.

2. The ridge jump is coincident with a broad fold producing a gentle seafloor ridge (Figure 2). Seismic reflection profiles across the ridge jump image folded sediment and associated small-scale faulting (Figures 6c and 6d). The igneous crust is slightly thicker to the south (e.g., line 10, Figure 6c). No onlap of strata on the basement is observed, whereas other gently dipping basement features show strata onlap (e.g., km 10–15 in Figure 6d). The upper half of the sediment section is hemipelagic [Kimura *et al.*, 1997], and therefore the distribution of the deposits is partially controlled by the topography of the ocean basement. For instance, the flat basement top between Fisher Ridge and the seamount to the south (Figure 6d) has a thin sediment cover, indicating some control from currents during sediment deposit. The folding and the seafloor ridge and the faulting and lack of onlap indicate recent tectonism, perhaps

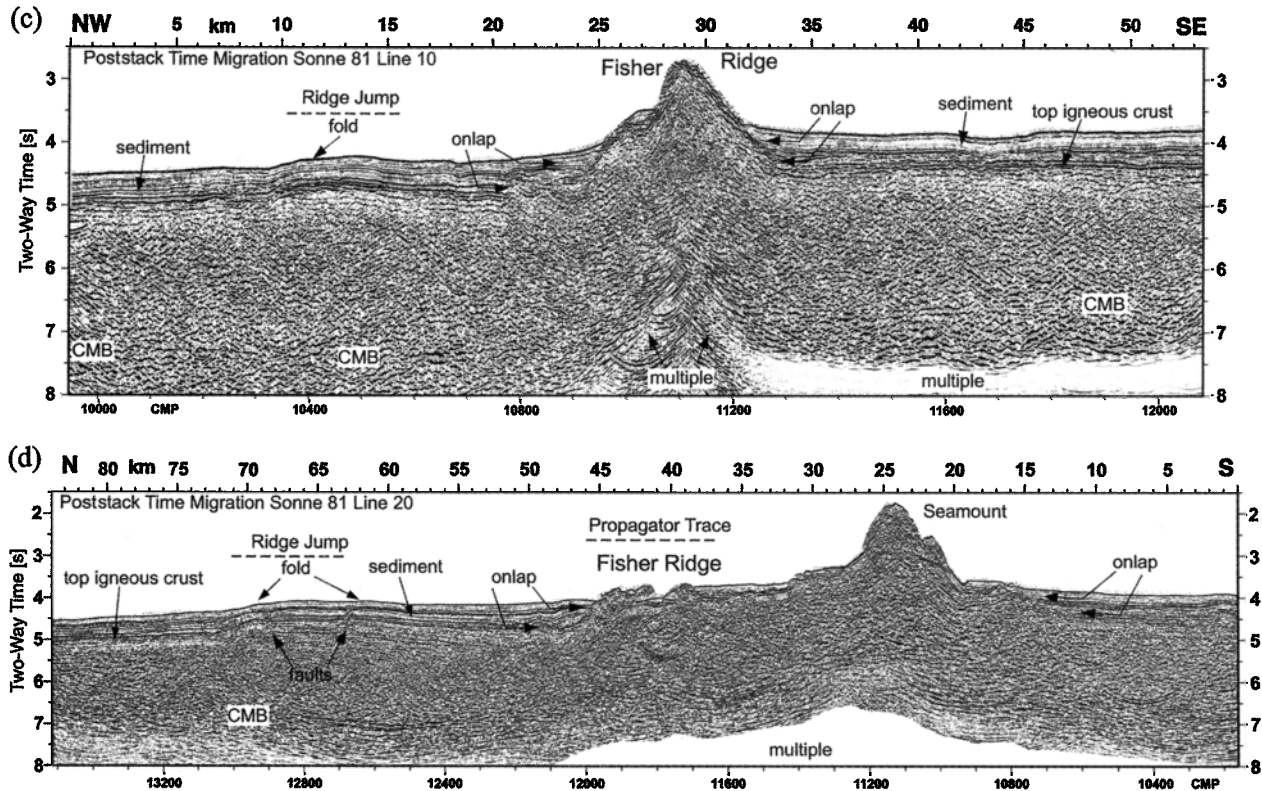
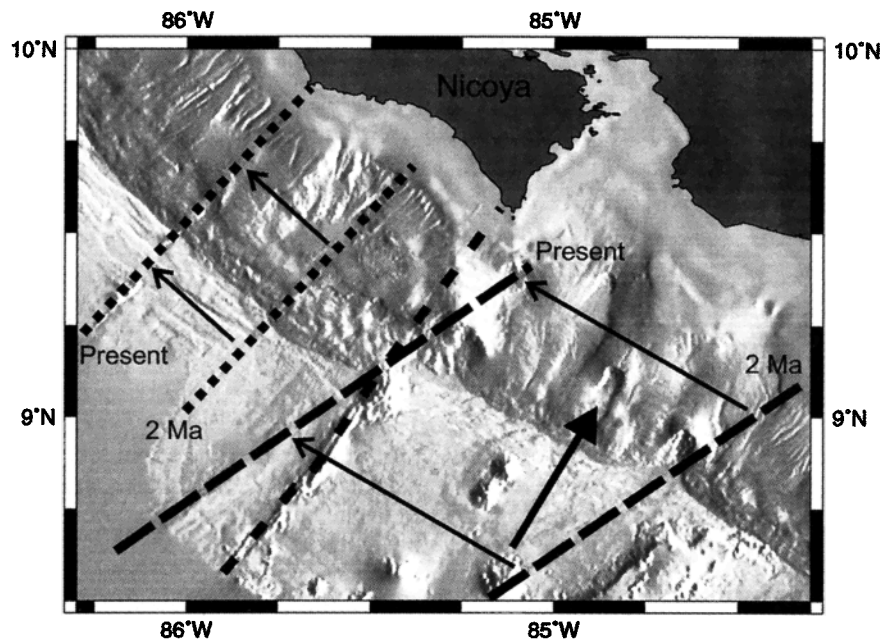


Figure 6. (continued)

created by reactivation along the structure during flexural bending of the subducting crust into the trench axis.

3. The propagator is associated with the ridge extending SW of Fisher Seamount (Figure 7), called Fisher Ridge. This ridge

probably formed later than the propagator during Miocene volcanism. Seismic images show down-to-the-NW displacement of all reflective horizons across the ridge (Figures 6c and 6d). Rock from Fisher Ridge is 19.2 m.y. old, equivalent in age



**Figure 7.** Movement of tectonic boundaries in the Cocos Plate along the Middle America Trench over the last 2 m.y. Thin arrows indicate the moving direction of the boundaries; the thick arrow shows the plate convergence direction. One of the three tectonic boundaries parallels the plate convergence vector and has remained stable with respect to the upper plate.

to the adjacent magnetic anomalies, and has a mid-ocean ridge basalt geochemistry [Werner *et al.*, 1999]. Conversely, Fisher Seamount is ~14 m.y. old ocean island basalt. Thus the ridge involves ruptured ocean crust and extrusion of lava. Strata on either side of Fisher Ridge and a seamount to the south have similar patterns of sediment onlap, indicating a similar age (Figures 6c and 6d; km 10–20). The ridge forms the northwestern boundary of an area flanking Cocos Ridge containing many seamounts like Fisher Seamount (Figure 2) with a Galapagos hot spot geochemistry [Werner *et al.*, 1999]. Fisher Ridge, Fisher Seamount, and the propagator are aligned with subducted seamounts extending landward under the slope and shelf to beneath the coast (Figure 2) [von Huene *et al.*, 2000]. These findings indicate that the fracture associated with the propagator probably continues across the ridge jump from CNS-1 to CNS-2 and into already subducted CNS-1 lithosphere. The current topography of the Fisher Ridge probably formed as ~5.5 m.y. old lithosphere was thermally thinned and domed during hot spot activity. It broke along the propagator, which probably focused magma extrusion at Fisher Seamount and related subducted seamounts in the chain. Vertical displacement across Fisher Ridge is the most prominent of all three tectonic boundaries (Figures 6c and 6d) and may explain the more prominent failure of the continental margin above its subducted extension. However, the propagator was inactive at the time this part of the Cocos Plate moved over the Galapagos hot spot (14 Ma) due to an earlier ridge jump to the south (CNS-2 to CNS-3). A plausible explanation is that the propagator fracture was reactivated by the hot spot event and extended into older lithosphere, where magmatism focused and formed the seamount chain. The landward projection of Fisher Ridge develops into the Quesada Sharp Contortion, a slab tear at a depth of 70 km beneath central Costa Rica [Protti *et al.*, 1995a]. Above it the volcanic arc is left-laterally offset across a gap (Figure 5).

The fracture zone trace and ridge jump are not aligned with such prominent structures in the continental crust as the propagator. This may be due in part to smaller crustal displacement and orientation with respect to the plate convergence vector. The collision point of the ridge jump migrated along the trench because its strike differs ~25° from the convergence vector. It migrated ~90 km to the northwest along the trench during the past 2 m.y. (Figure 7). The propagator parallels the convergence vector and thus has subducted at the same position with respect to the continent for some time. The angle between the fracture zone trace and the plate convergence vector is ~12°, resulting in migration to the northwest at ~20 km/m.y. Migration can explain the lack of prominent structure in the continental plate above the fracture zone trace and the ridge jump. However, the propagator subducted in the same area for at least 1–2 m.y., thereby affecting margin structure significantly. A major offset and division of the volcanic arc between Nicaragua and Costa Rica (Figure 5) [Carr and Stoiber, 1990] have no counterpart in the Cocos Plate and must be associated with an older continental crustal structure [von Huene *et al.*, 2000].

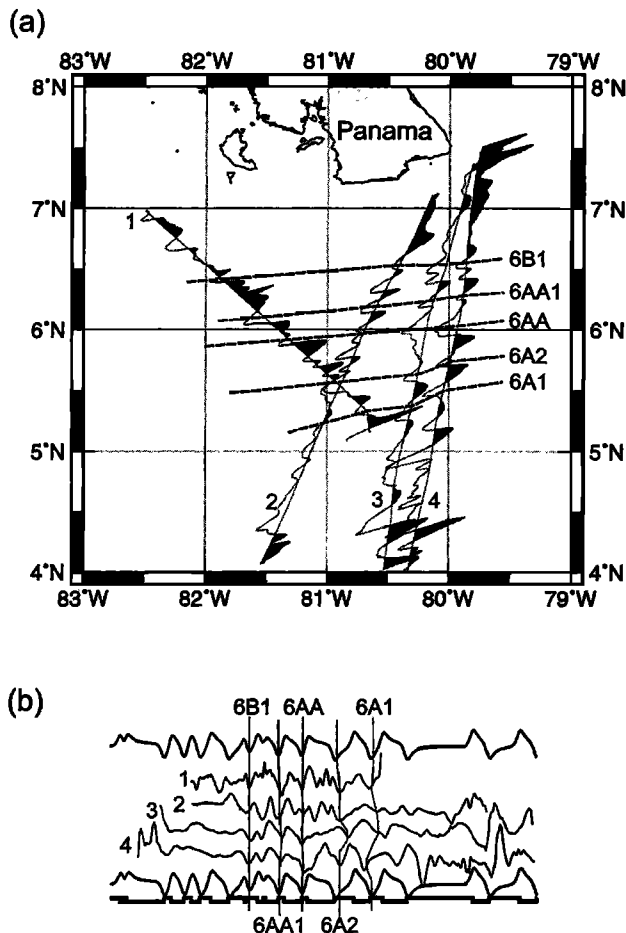
## 5.2. Implications for CNS History

The southern side of the CNS fracture zone trace coincides with the Grijalva Scarp (Plate 2). Hey [1977] stated that it is “an isochron that marks the time of origin of the Cocos Nazca spreading center and the rifting apart of the Farallon Plate to form the Cocos and Nazca plates.” We confirmed its age at 22.7 Ma (chron 6B1) and found its mirror image on the northern side of the CNS off Costa Rica. Off Costa Rica, only a

short section (~80 km) of this isochron remains unsubducted (Plate 2; anomalies are marked with red dashed lines), where it could only be detected with high-resolution magnetic mapping (Plate 1). The oldest CNS magnetic anomalies on the Nazca Plate are poorly resolved in the critical area between 89°W and 86°W because very few magnetic profiles lacking satellite navigation were acquired. However, detailed mapping of the mirror image of those anomalies off Costa Rica provides the key to reconstructing the early spreading history of the CNS. Spreading along CNS (CNS-1) began at 22.7 Ma, at a rate of ~95 mm/yr and with an almost symmetric accretion of new lithosphere to both sides of the rise (Figure 4). At 19.5 Ma the ridge jumped south, changing its strike direction by ~22° to nearly E-W (Plate 2; anomalies are marked with blue dashed lines). On the Cocos Plate, only the westernmost part of the area where the CNS-2 broke through the old pattern remains unsubducted. The spreading rate at the CNS-2 decreased to ~75 mm/yr and continued to be almost symmetric. The magnetic anomalies younger than C6 have higher amplitudes and are less regular in shape than the older anomalies, indicating an overall change in spreading conditions.

It is not clear exactly how long spreading at the CNS-2 continued. As explained earlier, because of the overprinting of the original pattern by the Cocos and Carnegie Ridges, major gaps remain in the identification of anomalies between 4A and 5C on both sides of the CNS. However, it is clear that during this period the accretion of crust was very asymmetrical [Hey, 1977]. In a previous model [Meschede *et al.*, 1998] the abandoned CNS-2 spreading center is presumed to coincide with a N70°E striking bathymetric feature and gravity low that can be traced from a position at 6°N, 88°W into the Cocos Ridge. The critical test of this model would be to find magnetic anomalies mirrored along this line. Unfortunately, a reliable correlation of anomalies on the northern flank of Cocos Ridge is difficult even with data from cruises SO-144/1 and SO-144/3. We presume that the original pattern of seafloor-spreading anomalies in this area was heavily overprinted during formation of Cocos Ridge. If the model of Meschede *et al.* [1998] were correct, then extrapolation from anomaly 5B southward provides a crustal age of ~14.5 m.y. along the abandoned spreading axis. Given that anomaly 5C is preserved on the Nazca Plate, the ridge jump from CNS-2 to CNS-3 must have transferred only ~60 km of crust (formed between 16.0 Ma and 14.5 Ma at a half-spreading rate of 40 mm/yr to the southern side of the CNS-2) from the Nazca to the Cocos Plate. If the ridge jump occurred later than 14.5 Ma, the amount of crust transferred may have been larger. It seems impossible at the moment to resolve the questions raised above. Therefore we suggest that at ~14.5 Ma a series of intermediate and small ridge jumps began which continue today [Wilson and Hey, 1995] and that this produces the asymmetrical accretion of lithosphere observed along the eastern part of the CNS.

On the basis of the identification of anomaly 6C in the northeastern Panama Basin, Lonsdale and Klitgord [1978] interpreted an older age for the initiation of Cocos-Nazca spreading than the 22.7 Ma given here. We reinvestigated the magnetic anomalies in the area south of Panama with a few magnetic profiles from the 1980s and one profile from cruise SO-144 (Figure 8). We find that the seafloor-spreading anomalies can be reasonably correlated with anomalies 6B1 through 6A1 (22.7–20.5 Ma) at a half-spreading rate of 50 mm/yr, which is in agreement with the findings off Costa Rica. Hence we suggest that the entire CNS opened at 22.7 Ma.



**Figure 8.** (a) Magnetic anomalies [NGDC, 1998; this study] in the northeastern Panama Basin shown as wiggles with positive anomalies shaded above the track line. Profiles with gray shaded anomalies are from the NGDC source; the profile with solid shaded anomalies is from the new data compiled here. The magnetic anomalies are derived from crust that was formed in the first phase of the CNS opening (CNS-1). (b) Correlation of the magnetic anomaly profiles shown in Figure 8a with a synthetic profile calculated from a 500 m thick source layer at 3500 m water depth with a half-spreading rate of 50 mm/yr.

### 5.3. Possible Influence of the Galapagos Hot Spot on Ridge Jumps

Formation of Cocos and Carnegie Ridges on the Cocos and Nazca plates from the Galapagos hot spot is widely accepted. Thus the ridges mark the azimuths of plate motion relative to the hot spot. In the simplest version of this model the hot spot activity has always been at the head of both ridges. However, the magnetic anomalies show that the spreading center repeatedly jumped over considerable distances. Other indications for a more complicated development of the submarine ridges are the difference in age between oceanic basement and seamounts on the flank of Cocos Ridge off Costa Rica, a depression in the Carnegie Ridge between 85°W and 87°W, and the present distance of ~170 km between the active spreading axis and the center of hot spot related volcanic activity. Today, the Cocos Plate moves in a northeasterly direction (N40°E), whereas the Nazca Plate moves nearly east [DeMets *et al.*, 1990]. This implies that as long as spreading is symmetric, the

CNS axis migrates northward. Even though both plates have not moved in a constant direction over the last 23 m.y., there is evidence that the situation, in general, has not changed during this time period [Mammerickx and Klitgord, 1982; Mayes *et al.*, 1990]. The identified ridge jumps and the asymmetry of crustal accretion at the CNS show a tendency for the CNS axis to jump southward toward the Galapagos hot spot, thus compensating for the northward migration. Müller *et al.* [1998] found many examples of asymmetric crustal accretion near hot spots in the South Atlantic, Indian Ocean, and southeastern Pacific. They concluded that randomly occurring small-scale ridge jumps can be biased by a nearby hot spot into successive ridge jumps toward the plume. The Galapagos hot spot and the CNS apparently also interact in this way. The Galapagos hot spot has been active during the past 23 m.y. and probably much longer [Hauff *et al.*, 1997]. It remains to be seen if the change from rare major ridge jumps in the early phase of the CNS history to more frequent small-scale ridge jumps after ~14.5 Ma is related to a change in the activity of the Galapagos hot spot.

## 6. Conclusions

With the data compiled here we located three tectonic boundaries in the Cocos Plate off Costa Rica.

1. We revised the position of the triple junction trace/fracture zone trace between EPR- and CNS-derived lithosphere. The position of this boundary is well defined with the new data, and it departs from the morphological rough-smooth boundary in the older part of the Cocos Plate. This is explained with high spreading rates during the early phase of CNS opening associated with the generation of smooth oceanic crust.

2. The revised magnetic anomalies revealed two spreading regimes in the early phase of CNS opening that are separated by a ridge jump at 19.5 Ma. The conjugate old CNS-derived magnetic anomalies on the Nazca Plate confirm that a wedge-shaped piece of lithosphere was transferred from Cocos to Nazca Plate by the ridge jump.

3. A prominent topographic feature on the Cocos Plate off Costa Rica, Fisher Ridge, corresponds with a propagator. We find indications that this propagator was reactivated during a phase of hot spot related volcanic activity and is again reactivated during the subduction of the Cocos Plate. Overprinting of the Cocos Plate by Galapagos hot spot volcanism is a second process that segments Cocos Plate off Costa Rica along with the complex plate tectonic history. The tectonic boundaries, seamount chains, and thickened crust of the hot spot trace define segments of the lower plate that appear to be related to a similar segmentation of upper plate tectonics and arc volcanism [von Huene *et al.*, 2000].

Detailed mapping of the oldest CNS seafloor-spreading anomalies off Costa Rica and additional identifications of magnetic anomalies older than 10 Ma allow refinement of the Hey [1977] model for early evolution of the CNS. Breakup of the Farallon Plate occurred at 22.7 Ma along a fracture zone striking ~65°E. The fracture zone trace separating EPR and CNS lithospheres currently intercepts the continent off Costa Rica. After a phase of rapid and symmetric spreading the spreading center jumped south at 19.5 Ma and changed its direction by 22°. Spreading remained symmetric at somewhat lower spreading rates. At ~14.5 Ma, another ridge jump to the south initiated a phase of frequent smaller southward ridge jumps that still continues. Half-spreading rates are symmetric across the CNS but increase eastward and let the Cocos Plate rotate



counterclockwise. The strong preference for ridge jumps in the southern direction implies that the Galapagos hot spot is a driving force for frequent ridge jumps and the resulting asymmetric crustal accretion.

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